

# Top Quark Pair Production Cross Section at the Tevatron

---

**Reinhild Yvonne Peters<sup>\*†</sup>**

*The University of Manchester, also at DESY  
School of Physics and Astronomy, Oxford Road  
Manchester M13 9PL  
England  
E-mail: repeters@cern.ch*

The top quark, discovered in 1995 by the CDF and D0 collaborations at the Tevatron proton antiproton collider at Fermilab, has undergone intense studies in the last 20 years. Currently, CDF and D0 converge on their measurements of top-antitop quark production cross sections using the full Tevatron data sample. In these proceedings, the latest results on inclusive and differential measurements of top-antitop quark production cross sections at the Tevatron are reported.

*The European Physical Society Conference on High Energy Physics  
22–29 July 2015  
Vienna, Austria*

---

<sup>\*</sup>Speaker.

<sup>†</sup>on behalf of the CDF and D0 Collaborations.

## 1. Introduction

Discovered more than 20 years ago, in 1995, by the CDF and D0 collaborations [1, 2] at the Fermilab Tevatron proton antiproton collider, the top quark is the heaviest elementary particle known today. Its high mass might indicate that it plays a special role in electroweak symmetry breaking and makes it a promising candidate as window to new physics. The detailed study of the top quark and its production mechanism is therefore crucial.

In this article, measurements of top-antitop quark production ( $t\bar{t}$ ) cross sections, performed by CDF and D0 in Run II of the Tevatron, are discussed. In Run II, lasting from 2001 to 2011, the collision energy was 1.96 TeV. The measurements of inclusive  $t\bar{t}$  cross sections and their comparison to predictions from quantum chromodynamics (QCD) calculations allows to test the standard model (SM) in detail. Many new physics models with final states similar to that of  $t\bar{t}$  production would change the measured cross sections significantly. Furthermore, differential measurements of  $t\bar{t}$  cross sections are reported, which serve as test for perturbative QCD (pQCD) predictions, can be used to tune Monte Carlo simulations, and are a useful tool to look for new physics that would change the shape of kinematic or topological variables relative to the SM prediction.

## 2. Inclusive Cross Section Measurements

The production of  $t\bar{t}$  pairs occurs via the strong interaction. At the Tevatron, approximately 85% of the  $t\bar{t}$  production happen via quark-antiquark annihilation, and 15% via gluon-gluon fusion. These proportions are approximately inverted at the LHC. This means that the sensitivity to beyond the SM (BSM) physics scenarios is different at Tevatron and LHC.

The measurement of the  $t\bar{t}$  cross section is done separately in different final states. In the SM, the top quark decays almost 100% of the time into a  $W$  boson and a  $b$  quark, with the  $W$  either decaying into a quark-antiquark pair, or a charged lepton and the corresponding neutrino. The event selection in each decay channel is adjusted to the respective final state objects, with the goal to enhance the data sample with  $t\bar{t}$  events and reduce the background, while keeping a reasonable statistics. The decay channels considered are usually the dilepton final state, where both  $W$  bosons decay into electrons, muons or leptonically decaying taus, the semileptonic final state, with one  $W$  boson decaying into electron, muon or leptonically decaying tau, and the other  $W$  boson into quarks, and the fully hadronic final state, in which both  $W$  bosons decay into quarks. In the dilepton final state a low background can be achieved, but the branching fraction is small, while allhadronic events represent a large branching fraction, but a large background. The best mixture for most analyses is usually the semileptonic channel, which mixes a good branching fraction with a manageable background. Depending on the channel, different approaches to the measurement of the cross section are done. In very clean channels usually a counting-method is sufficient, while less clean ones require the use of multivariate analysis techniques, in which several variables with small signal-to-background separation are combined into one discriminant. Given the two  $b$ -jets in the  $t\bar{t}$  final state, a useful tool often applied is  $b$ -tagging, where properties of displaced tracks and secondary vertices from the  $B$  hadron decay are considered to identify jets from  $b$  fragmentation.

In this article, analyses in these three main final states are presented. The main background contribution in dileptonic events comes from  $Z$ +jets processes, which can be simulated using Monte

Carlo (MC) generators. In semileptonic events, the handling of the largest background contribution,  $W$ +jets, is done using simulated events and normalizing the yield using a data-driven approach. For multijet events, the largest contribution comes from QCD multijet events, which require data-driven modelling of the background. Further, smaller background contributions are single top, diboson and fake events, where the latter are events coming from jets misidentified as leptons in the detector.

## 2.1 Tevatron Combination

In 2014, CDF and D0 published the first combination of the  $t\bar{t}$  cross section from both collaborations, using data samples between 2.9 and 8.8 fb<sup>-1</sup>. In particular, four analyses from CDF and two from D0 were used in the combination. CDF provided one analysis in the dilepton final state, where the number of events with at least one  $b$ -tagged jet was counted, two analyses in semileptonic events, where the number of events with at least one  $b$ -tagged jet was counted or a Neural-Network discriminant [3] was built based on kinematic variables. The fourth analysis, in the allhadronic final state, used events with exactly one or at least one  $b$ -tagged jet, performing a maximum likelihood fit to the reconstructed top quark mass. The D0 collaboration provided an analysis in the dileptonic final state, where a likelihood fit to a discriminant based on a Neural-Network  $b$ -tagging algorithm, was performed, and an analysis in the semileptonic final state was performed, in which events with three and more than three jets were split into events with zero, one or at least two  $b$ -tagged jets. For signal dominated sub-channels a simple counting method was then used, while in background-dominated sub-channels a random forest discriminant was applied.

The CDF analyses were combined using BLUE [4], while the D0 analyses were fitted simultaneously with a likelihood fit, where the systematic uncertainties were treated as nuisance parameters. These two experiment-specific combinations were then combined in a further step using BLUE, resulting in a  $t\bar{t}$  cross section of  $\sigma_{t\bar{t}} = 7.60 \pm 0.41$  (stat + syst) pb [5] for a top quark mass of 172.5 GeV. This result is compatible with the SM prediction of  $\sigma_{t\bar{t}} = 7.35^{+0.23}_{-0.27}$  (scale + pdf) pb, calculated at next-to-next-to-leading order (NNLO) precision in QCD, with soft-gluon resummation to next-to-next-to-leading logarithmic accuracy [6]. The cross section measurements in different channels are compatible with each other, showing no evidence for possible BSM contributions. Figure 1 shows the  $t\bar{t}$  cross sections in the different channels by the two experiments, as well as the combination.

## 2.2 New D0 result

Using the full Tevatron data sample of 9.7 fb<sup>-1</sup>, the D0 collaboration recently updated their inclusive measurement of the  $t\bar{t}$  production cross section in the dileptonic and semileptonic final states. The analysis strategy is similar to the one used for the Tevatron combination: in dileptonic events, the discriminant trained for  $b$ -jet identification via a multivariate analysis technique is used to discriminate  $t\bar{t}$  signal from the background. A template fit is performed to extract the cross section value. In semileptonic events, a topological discriminant, based on boosted decision trees (BDTs), is trained separately for events with two, three or at least four jets, and the cross section is extracted by simultaneously performing a maximum likelihood fit on the discriminants in these three sub-channels. The resulting cross section is  $\sigma_{t\bar{t}} = 7.73 \pm 0.13$  (stat)  $\pm 0.55$  (syst) pb [7], in good agreement with the SM prediction. The main contribution to the systematic uncertainties comes from modelling of the hadronization.

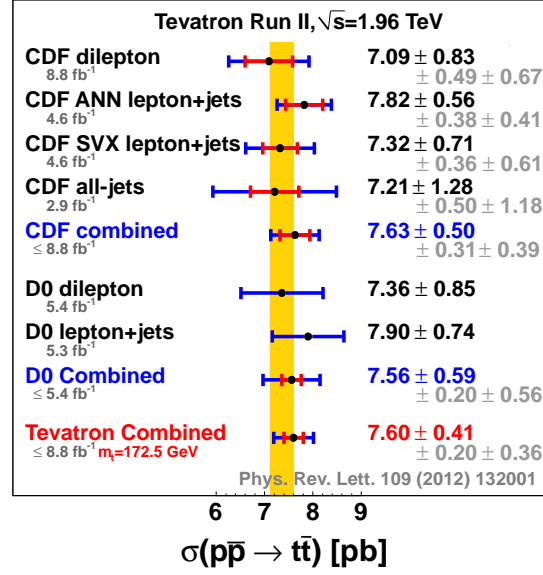


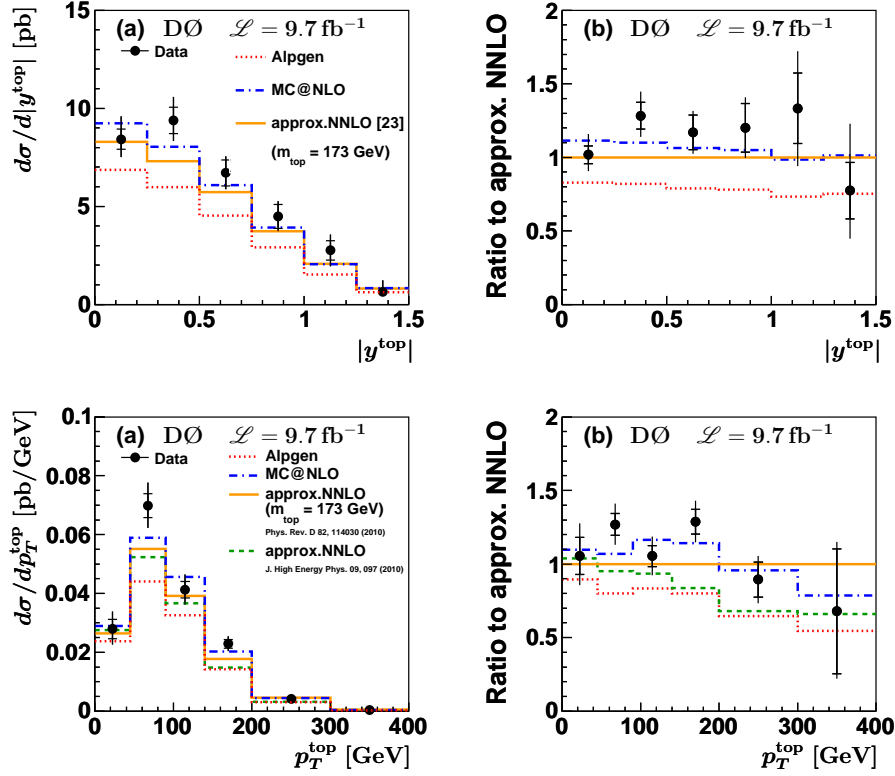
Figure 1: Tevatron combination of the  $t\bar{t}$  cross section by the CDF and D0 collaborations [5].

### 3. Differential Cross Section Measurements

Besides performing measurements of inclusive cross sections, the determination of the  $t\bar{t}$  cross section differentially as function of various variables is important. Differential  $t\bar{t}$  cross section measurements provide a test of pQCD, help to tune the simulation of  $t\bar{t}$  events, and can yield additional insight into potential hints for new physics. For example, deviations in the  $t\bar{t}$  cross section as function of the invariant  $t\bar{t}$  mass,  $m_{t\bar{t}}$ , could yield insight into the existence of heavy resonances decaying into a pair of top quarks, or possible new physics contributions to the  $t\bar{t}$  forward-backward asymmetry can be probed by measuring differential distributions in variables related to the pseudorapidity of the top quark.

Using the full Run II data sample of 9.7 fb<sup>-1</sup>, D0 recently performed a measurement of the  $t\bar{t}$  cross section as function of three variables:  $m_{t\bar{t}}$ , the absolute value of the rapidity of the top quark,  $|y^{top}|$ , and the transverse momentum of the top quark,  $p_T^{top}$  [8]. The analysis was performed in the semileptonic final state, with at least one jet required to be  $b$ -tagged. The calculation of the variables  $|y^{top}|$  and  $p_T^{top}$  requires the assignment of final state objects to originate from the top or the antitop quark. For this assignment, a constrained kinematic reconstruction algorithm [9] is used, in which experimental resolutions are taken into account. In this algorithm, the top quark mass and  $W$  boson mass are fixed to their known values, allowing to determine the  $z$ -component of the neutrino momentum from the  $W$  boson mass constraint and reducing the number of possible jet-quark assignments via the top quark mass constraint. The solution with the best  $\chi^2$  is taken for the construction of the top quark vectors.

The measurement is defined for parton-level top quarks, including off-shell effects. Therefore, a correction for detector and acceptance effects has to be done. A regularized unfolding, implemented in TUNFOLD [10], is used for this purpose, where the regularization is based on the derivative of the distributions. To keep as much information as possible, the number of bins for the reconstructed distributions is kept twice as high as the number of bins on parton



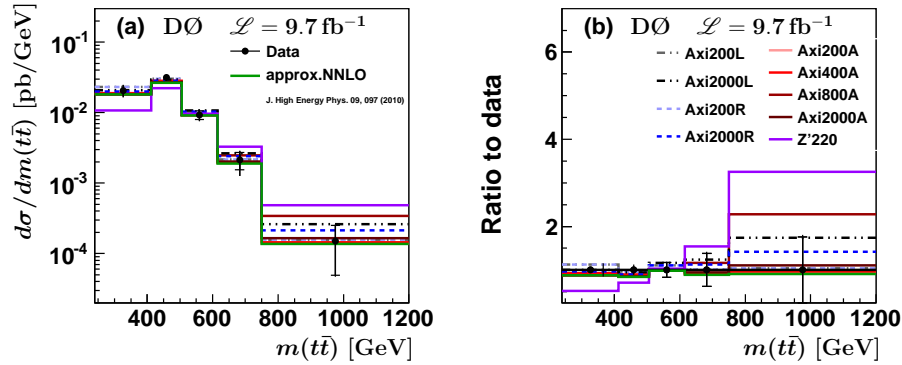
**Figure 2:** The  $t\bar{t}$  cross section measured as function of  $|y^{top}|$  (top), and  $p_T^{top}$  (bottom). The left figures show the cross section, the right figures the ratio of the measured cross section with respect to the approximate NNLO calculation [8].

level. The contribution of different sources of systematic uncertainties are evaluated by changing the migration matrix and the background contribution. The largest uncertainties arise for high bins in  $m_{t\bar{t}}$ ,  $|y^{top}|$ , and  $p_T^{top}$ . In Figure 2 the measured  $t\bar{t}$  cross section differentially in  $|y^{top}|$ , and  $p_T^{top}$  is shown, together with predictions from Monte Carlo simulation and predictions from approximate NNLO calculations. In general, the agreement is good relative to the generator and approximate NNLO predictions. For ALPGEN [11], the absolute normalization is too low, while in the  $|y^{top}|$  variable the description by the MC@NLO generator [12] is better than that of the approximate NNLO prediction.

The  $t\bar{t}$  forward-backward asymmetry has been measured by both CDF and D0 in recent years to be somewhat larger than predicted by the SM [13]. In many BSM models, for example  $Z'$  or axigluon models, this asymmetry would be associated to a change in differential distributions. Figure 3 shows the differential  $t\bar{t}$  cross section as function of  $m_{t\bar{t}}$ , compared to different axigluon and a  $Z'$  model. The measurement excludes several of these models.

#### 4. Conclusion and Outlook

The measurements of the inclusive and differential  $t\bar{t}$  cross sections using the full data samples collected by the CDF and D0 collaborations at the Tevatron is moving towards its completion.



**Figure 3:** The  $t\bar{t}$  cross section measured as function of  $m_{t\bar{t}}$  and compared to various axigluon models [8].

These legacy measurements are important to test the SM, tune Monte Carlo simulations and search for hints of new physics. The different initial state and energy of the Tevatron compared to the LHC, make these complementary measurements.

## Acknowledgments

I thank my collaborators from CDF and D0 for their help in preparing the presentation and this article. I also thank the staffs at Fermilab and collaborating institutions, and acknowledge the support from the Helmholtz association.

## References

- [1] F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **74**, 2626 (1995).
- [2] S. Abachi *et al.* [D0 Collaboration], Phys. Rev. Lett. **74**, 2632 (1995).
- [3] A. Hocker *et al.*, PoS (ACAT) 040 (2007).
- [4] L. Lyons, D. Gibaut and P. Clifford, Nucl. Instrum. Methods in Phys. Res. Sect. A **270**, 110 (1988); L. Lyons, A. Martin and D. Saxon, Phys. Rev. D **41**, 3 (1990); A. Valassi, Nucl. Instrum. Methods in Phys. Res. Sect. A **500**, 391 (2003).
- [5] T. Aaltonen *et al.* [CDF and D0 Collaborations], Phys. Rev. D **86**, 092003 (2012).
- [6] P. Barnreuther, M. Czakon and A. Mitov, Phys. Rev. Lett. **109**, 132001 (2012).
- [7] The D0 Collaboration, D0 Note 6453-CONF (2015).
- [8] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **90**, 092006 (2014).
- [9] S. Snyder, Doctoral Thesis, State University of New York at Stony Brook (1995).
- [10] S. Schmitt, JINST **7**, T10003 (2012) [arXiv:1205.6201].
- [11] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. D. Polosa, J. High Energy Phys. **07**, 001 (2003).
- [12] S. Frixione, B.R. Webber, J. High Energy Phys. **06**, 029 (2002).
- [13] J.A. Aguilar-Saavedra, D. Amidei, A. Juste, M. Perez-Victoria, arXiv:1406.1798 [hep-ph] (2014).